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A systematic review on the sources and health risk of heavy metal contamination in environmental and food systems in Uganda

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Abstract

This study systematically reviewed research on heavy metal contamination in environmental and food systems in Uganda using the PRISMA 2020 data reporting method and the PICOS framework. An extensive literature search of published papers on heavy metal contamination in Uganda's environment and food systems was conducted in PubMed, Web of Science, and Scopus databases up to May 21, 2024. Boolean operators (AND/OR/NOT) were applied to develop search strategies tailored to each database. Following duplicate removal, title and abstract screening, and full-text assessment using the Rayyan platform, 39 articles were included in the final review. Data were extracted from each study using a standardized template that captured metal type, contamination source, concentration levels, affected food or environmental matrix, geographic location, and toxicological impact. Data were synthesized using a descriptive and narrative approach. Key sources of contamination include industrial and municipal waste, agricultural practices, and emissions from transport and manufacturing. Among the metals, lead was the most mentioned across studies. Regional analysis revealed that Central Uganda had the highest reports on heavy metals, while Northern Uganda remains critically understudied. Ecologically, heavy metals threaten soil fertility, aquatic biodiversity, and agricultural sustainability. Contamination of staple foods with lead, cadmium, and mercury poses significant public health risks, particularly for children and pregnant women. Strengthened environmental monitoring, targeted regional investigations, and improved food safety surveillance within a One Health framework are urgently recommended.

Keywords: Environmental health, Food safety, Heavy metal contamination, Lead toxicity, Uganda

1 Introduction

A recent investigation by [15] revealed that Uganda, renowned for its abundant biodiversity and scenic landscapes, is now grappling with the emergence of heavy metal contamination, which provides substantial risks to the country's ecological communities and public health. Nantaba et al. [55] buttress that the analysis of the geographical distribution and quantities of these heavy metals in various habitats is crucial for elucidating hazards and developing efficient management interventions. Heavy metals, by virtue of their potential for bioaccumulation, are particularly problematic as they can contaminate water bodies, soils, and the food chain, resulting in adverse well-being outcomes. The inadequate management and disposal of expired pharmaceuticals, electronic trash, and industrial effluents contribute to the environmental burden of heavy metals [86].

In addition, urban stormwater carries a variety of pollutants, including heavy metals, into surface waters, a considerable public health issue because these metals can accumulate in the bodies of living animals [4, 81]. Additionally, the inadequate recycling and uncontrolled incineration of electronic debris release harmful chemicals into the environment, further exacerbating contamination. The health implications of heavy metal exposure are profound, with children in Uganda already showing alarmingly high blood levels of metals such as manganese (Mn) and lead (Pb), which may result in neurodevelopmental impairments [15]. Recent studies have shown that elevated levels of environmental heavy metals are a prevalent concern among children in Africa, with the Katanga settlement in Kampala, Uganda, serving as a prime example [28]. A sample of healthy Ugandan children extracted from a neighbourhood within this area revealed alarmingly high blood levels of metals such as antimony (Sb), copper (Cu), cadmium (Cd), cobalt (Co), Pb, and Mn. Pb and Mn affected 97.0% and 36.4% of the children tested, respectively [28]). This exposure is concerning given the potential neurodevelopmental limitations it could impose on the affected children.

The rise in industrialization in Uganda, mirroring trends across sub-Saharan Africa and other low-income countries, is a significant contributor to this environmental contamination [28], express concern that the lack of stringent regulations and mitigation strategies exacerbates heavy metal contamination. This extends beyond the environment into the food supply, thereby increasing human health risk. Investigations conducted by [56] detected heavy metals, including zinc (Zn), Cr, Cd, Cu, Iron (Fe), Co, nickel (Ni), and Pb, in beef sourced from Eastern Uganda. These findings have raised concerns over the safety of the consumption of meat in this area. The existence of these metallic elements in food can be ascribed to the feedlots and water used in raising livestock [24].

To protect public health, the World Health Organization (WHO) has set daily and weekly intake guidelines for certain metals [112]. For instance, the recommended daily intake for Fe is 6 ppm/day for children and 392 ppm/week for a 70 kg adult, while for Cu, it is 1 ppm for children and 245 ppm/week for adults [56]. However, a high intake of metals like copper may result in severe health issues, such as intestinal ulcerations and kidney problems [97]. Elements including Pb, Cd, Ni, and Cr are harmful and carcinogenic [5]. In Uganda, however, data on heavy metal pollution levels remain limited. This constrains policymakers' implementation of evidence-based protective measures [28]. The findings from these previous studies by [28, 5] highlight the urgent need to develop comprehensive strategies to address heavy metal pollution in Uganda.

As Uganda continues to develop industrially, measures must be taken to protect citizens and the environment from the impacts of toxic metals. Thus, this study systematically evaluated the heavy metal contamination in environmental and food systems in Uganda from 2014 to 2024 using the PRISMA guidelines of data reporting and the PICOS framework. The PRISMA method is a critical tool for enhancing the quality and transparency of meta-analyses and systematic reviews [43]. Its comprehensive checklist and flow diagram help ensure that reviews are thoroughly reported, making them more reliable and reproducible [97]. This review presented a comprehensive analysis of the current state, origins, and effects of heavy metal contamination in the country. This comprehensive approach is critical for the long-term sustainability of the environment and safeguarding public health. Furthermore, it provides policymakers, researchers, and stakeholders with essential knowledge, guiding the creation of evidence-based policies and promoting environmentally friendly behaviors to protect Uganda's environmental assets.

2 Materials and methods

2.1 Search strategy and database selection

A comprehensive literature search of published articles on heavy metal contamination in Uganda's environment and food system was systematically conducted across PubMed, Web of Science (WoS), and Scopus databases up to May 21, 2024. The search utilized the following terms: "heavy metal," "environment," "food," and "Uganda." Boolean operators (AND/OR/NOT) were applied to develop search strategies tailored to each database, as outlined by [37, 35, 36]. The search was restricted to peer-reviewed articles published in English. The paper selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [97], as referenced by [75] (Table 1).

2.2 Selection criteria

The following inclusion criteria were applied for articles to be selected for the study: studies that report heavy metal (mercury, lead, chromium, copper, cadmium, arsenic,

Table 1 Search strategies

Database	Search strategy
Scopus	TITLE-ABS-KEY (metal* OR mercury OR copper OR lead OR chromium OR cadmium OR arsenic OR thallium OR beryllium OR nickel OR aluminum OR zinc OR cobalt OR vanadium) AND (environment* OR surrounding* OR ecosystem OR habitat* OR food*) AND (Uganda*)
WoS	((metal* OR mercury OR copper OR lead OR chromium OR cadmium OR arsenic OR thallium OR beryllium OR nickel OR aluminum OR zinc OR cobalt OR vanadium) AND (environment* OR surrounding* OR ecosystem* OR habitat* OR food*) AND (Uganda*) Title
PubMed	((metal*[Title/Abstract]) OR (mercury[Title/Abstract]) OR (copper[Title/Abstract]) OR (lead[Title/Abstract]) OR (chromium[Title/Abstract]) OR (cadmium[Title/Abstract]) OR (thallium[Title/Abstract]) OR (beryllium[Title/Abstract]) OR (nickel[Title/Abstract]) OR (aluminum[Title/Abstract]) OR (cobalt[Title/Abstract]) OR (vanadium[Title/Abstract]) OR (zinc[Title/Abstract]) OR (arsenic[Title/Abstract])) AND ((environment*[Title/Abstract]) OR (surrounding*[Title/Abstract]) OR (ecosystem*[Title/Abstract]) OR (habitat*[Title/Abstract]) OR (food*[Title/Abstract])) AND (Uganda[Title/Abstract]) NOT (review[Publication Type]))

thallium, beryllium, nickel, aluminum, cobalt, zinc, vanadium) contamination, studies involving any environment or food system, studies emanating from Uganda only, and peer-reviewed articles published in English. The exclusion criteria set for the screening and selection included: Studies focusing on other metals aside from mercury, lead, chromium, cadmium, arsenic, thallium, beryllium, nickel, aluminum, cobalt, zinc, vanadium, and arsenic, studies on the impact of heavy metals on any other system aside environment and food, studies that do not clearly define the impact of heavy metals on environment and food, non-English publications, review articles, editorials, commentaries, book chapters and conference abstracts. The data extracted from each of the included studies are: Type of heavy metal, possible source, level of contamination, type of food impacted, district and region, toxicological impact, and year of publication.

2.3 Study selection and screening

Screening was conducted independently by two reviewers across two sequential stages. In the first stage, both reviewers independently screened all records at the title and abstract level against the predefined PICOS eligibility criteria. Records that clearly did not address heavy metal contamination in Uganda's environmental or food systems up to 2024, or did not meet the required study design criteria, were excluded at this stage. To minimize the risk of erroneous exclusion, any record for which eligibility could not be confidently determined from the title and abstract alone was retained and advanced to full-text review.

In the second stage, full-text PDF files of all retained records were retrieved and uploaded into Rayyan for detailed independent assessment by both reviewers. Each full-text article was evaluated against the complete set of eligibility criteria. Studies were excluded at this stage for the following reasons: conducted outside Uganda, absence of original heavy metal concentration or source data, non-peer-reviewed or grey literature sources, and studies focusing exclusively on contaminants other than heavy metals.

At both screening stages, discrepancies in inclusion or exclusion decisions between the two reviewers were initially addressed through discussion and mutual re-evaluation of the relevant eligibility criteria. Where disagreement persisted following discussion, a third independent reviewer was consulted, and their decision was accepted as final. Studies satisfying all eligibility criteria following completion of both screening stages were included in the final qualitative synthesis, covering soils, water bodies, air, agricultural produce, fish, beef, and processed food products across Uganda's four administrative regions.

2.4 Data extraction

Data extraction was performed systematically for each included study using a standardized extraction template. The following variables were extracted from each study: type of heavy metal reported, possible contamination source, level of contamination, type of food or environmental matrix impacted, district and region of study, toxicological impact, and year of publication. Extracted data were tabulated and verified by a second reviewer to ensure accuracy and consistency across all included studies.

2.5 Data synthesis and analysis

Data were synthesized using a descriptive and narrative approach. Extracted variables were tabulated, summarized, and grouped by metal type, food category, and geographic region to identify patterns, trends, and key sources of contamination across the included studies. Thematic analysis was applied qualitatively to interpret findings across these groupings.

To characterize the regional distribution of heavy metal contamination, the reporting counts for each metal were recorded by region in Uganda across all included studies. A single study could contribute multiple metal reports if two or more metals were documented within a given region. The regional percentage for each metal was calculated by dividing the number of times that metal was reported in a specific region by the total number of metal reports across all regions and studies, then multiplying by 100. This approach provides a relative measure of each metal's contribution to the overall national contamination reporting burden rather than an absolute concentration estimate. The regional total percentage was derived by summing all metal report counts within a given region, dividing by the national total, and multiplying by 100. National-level percentages for the reported metals were calculated by summing their mentions across all four regions and dividing by the same national total.

2.6 Quality and risk of bias assessment

The methodological quality of the included studies was assessed using the Appraisal Tool for Cross-Sectional Studies (AXIS). The assessment focused on five domains: study objectives, sampling methods, measurement validity, statistical analysis, and consideration of confounding factors. Each domain was rated as having either low or moderate risk of bias, and an overall risk-of-bias judgment was assigned for each study. Two reviewers independently conducted the assessment, and disagreements were resolved through discussion. The results were visualized using the Robvis tool under the generic risk-of-bias model.

The AXIS assessment indicated that all included studies had clearly defined objectives and appropriate measurement procedures. Most studies demonstrated low risk of bias in sampling and statistical analysis domains, although a subset of older studies showed moderate concerns related to sample representativeness and reporting of analytical procedures (Fig. 1). Confounding factors were the most frequently identified source of methodological concern, with many studies providing limited discussion of potential environmental and socio-demographic confounders. Overall, 30 studies (78.9%) were classified as having a low risk of bias, while nine studies (21.1%) were classified as having a moderate risk of bias (Fig. 2a and b). No study was categorized as having a high risk of bias.

3 Results

3.1 Search results

The search identified a total of 1094 articles, comprising 563 articles from WoS, 395 from Scopus, and 136 articles from PubMed. The articles were uploaded to the Rayyan platform for screening and selection. Rayyan is an online application for systematic review methodology [43]. Using the platform, 354 duplicates were detected.

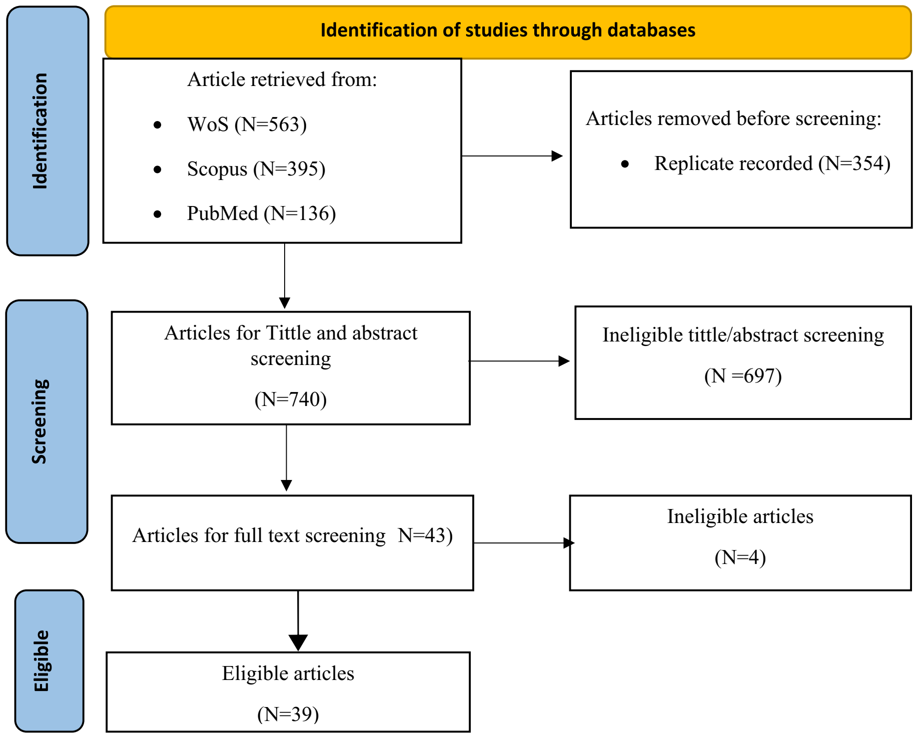

Fig. 1 PRISMA flow chart for study selection

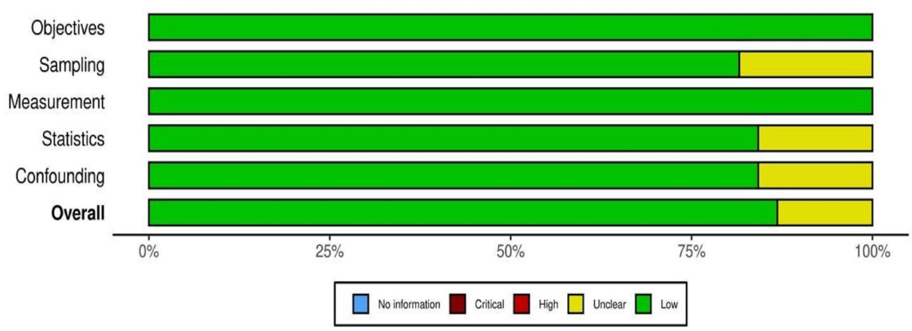

Fig. 2 **a** Summary Plot Showing Risk of Bias Assessment. **b** Traffic Plot Showing Risk of Bias Assessment. Risk of Bias Assessment Summary across 39 Included Studies. Risk of bias was assessed using the AXIS tool across five domains (objectives, sampling, measurement, statistics, confounding). The figure summarises domain-level and overall risk judgments for all included studies. Two independent reviewers rated each domain as low, moderate, or high risk. No study was rated as high risk overall

Deduplication was done appropriately. A total of 740 articles were screened via title/abstract consideration and full-text screening sequentially, in accordance with the eligibility criteria. Eventually, only 39 articles were reviewed in the study, having passed the eligibility criteria (Fig. 1).

3.2 Risk of bias results

The included studies generally demonstrated a low-to-moderate risk of bias due to the use of laboratory-based analytical methods, defined eligibility criteria, independent screening, and standardised data extraction procedures. However,

Fig. 2 continued

moderate bias was observed because most studies were concentrated in Central and Western Uganda, with limited representation from Northern Uganda. Variations in sampling methods, analytical techniques, and reporting standards also introduced measurement bias and limited comparability across studies. In addition, many studies did not adequately control environmental and anthropogenic confounding factors. Overall, the evidence was considered moderately reliable, although methodological heterogeneity and geographic imbalance may affect the generalizability of the findings across Uganda.

3.3 Regional distribution of heavy metal reporting across Uganda

The regional and national percentage distribution of the heavy metal mentioned across the included studies are presented in Table 2. Analysis of the regional distribution of heavy metal reporting across the 39 included studies revealed marked geographic disparities in research coverage, with the Central region accounting for the highest number of metal mentions (n = 30), followed by the Western (n = 21), Eastern (n = 15), and Northern (n = 1) regions, collectively totalling 67 metal mentions nationwide (Table 2).

The Central region dominated the reporting profile, with Pb mentioned most frequently (n = 8), followed by Cu (n = 5), Cd (n = 4), and Cr, Ni, and Zn each mentioned three times. The Western region similarly recorded a diverse reporting profile, with Cd, Cu, Pb, and Zn each mentioned three times, alongside contributions from Cr, Ni, Fe, and Co, reflecting documented research interest in the region's mining, oil exploration, and industrial effluent-related contamination [28, 84]. Eastern Uganda showed a comparatively uniform distribution, with most metals mentioned only once across the included studies. Northern Uganda was strikingly underrepresented, with only a single mention of aluminium across all 39 included studies. At the national level, Pb accounted for the largest share of all metal mentions (17.9%), indicating that it has received the greatest research attention among all metals documented in Uganda, followed by Cu (13.4%), Cd (11.9%), Cr and Zn (10.4% each), and Ni (9.00%). Mercury accounted for 6.00% of national mentions.

3.4 Identity and sources of heavy metals in Uganda

The identity and sources of the metals reported are presented in Table 3.

The included studies collectively identified 13 heavy metals across Ugandan environments, food systems, and ecological settings, namely lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), nickel (Ni), zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), aluminium (Al), arsenic (As), cobalt (Co), and selenium (Se) (Table 3). Among

Table 2 Percentage of heavy metal reports from the included studies by regions

Region	As	Cd	Cr	Cu	Ni	Pb	Zn	Fe	Mn	Co	Hg	Se	Al	Regional total (%)
Central	1.50	6.00	4.50	7.50	4.50	11.9	4.50	–	1.50	–	3.00	–	–	44.8
Western	–	4.50	3.00	4.50	3.00	4.50	4.50	3.00	–	1.50	1.50	–	1.50	31.3
Eastern	1.50	1.50	3.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	3.00	22.4
Northern	–	–	–	–	–	–	–	–	–	–	–	–	1.50	1.50
National (%)	3.00	11.9	10.4	13.4	9.00	17.9	10.4	4.50	3.00	3.00	6.00	1.50	6.00	100

Values represent the percentage of each metal's regional report count relative to the total national report count (n = 67). All values expressed as %

Al Aluminium, *As* Arsenic, *Cd* Cadmium, *Cr* Chromium, *Cu* Copper, *Ni* Nickel, *Pb* Lead, *Zn* Zinc, *Fe* Iron, *Mn* Manganese, *Co* Cobalt, *Hg* Mercury, *Se* Selenium.

Table 3 Heavy metals and sources as reported in the included articles

Heavy metal	Specific sources	References
Lead (Pb)	Industrial/municipal waste, lead-based paints and gasoline, battery and metal fabrication, vehicle emissions, fossil fuel burning, mining, urban runoff, agricultural practices, cookware materials, waste disposal, soil erosion	[40, 114, 14, 57, 16, 17, 43, 64, 77]
Cadmium (Cd)	Paints, textiles, batteries, metal manufacturing, fossil fuel burning, vehicle emissions, agricultural runoff, dumpsites, urban pollution, waste disposal, soil erosion	[28, 43, 64, 77, 81, 14]
Mercury (Hg)	Atmospheric deposition, agricultural runoff, battery disposal/burning, vehicle emissions, sand mining, metal welding, industrial/domestic waste, fertilizers and pesticides, natural processes	[44, 27, [8, 95]
Manganese (Mn)	Industrial/municipal waste, mining activities, biomass burning, soil erosion, heavy traffic, oil exploration, charcoal burning, cookware materials, lake bed deposits	[14, 84, 28, 39]
Arsenic (As)	Aluminium scrap, manufacturing processes, unregulated waste disposal, wastewater irrigation, industrial emissions, fertilizers, Pb-containing paints and gasoline	[28, 113]
Chromium (Cr)	Industrial waste, mining, agronomic practices, manufacturing processes, cookware materials, wastewater irrigation, industrial emissions, fertilizers	[114, 28, 28]
Copper (Cu)	Copper mines, fabrication and welding activities, agronomic practices, industrial effluents, soil and water contamination, natural geological formations (shales, granites)	[58, 83, 79]
Aluminium (Al)	Anthropogenic emissions, artisanal gold mining, agricultural land use changes, wetlands, urban runoff, waste disposal	[39, 87]
Iron (Fe)	Steel production emissions, fossil fuel burning, mining and processing, phosphate fertilizers, animal manure, industrial waste	[57, 87, 96]
Zinc (Zn)	Copper mines, mine tailings erosion, underground mine water, urban pollution, agricultural runoff, natural geological formations, waste disposal	[33, 84, 28, 55]
Cobalt (Co)	Copper mining, oil exploration, charcoal burning, lake bed deposits	[33, 42]
Nickel (Ni)	Copper mines, mine tailings erosion, fabrication and welding activities, steel and iron industries, underground mine water	[56, 96]
Selenium (Se)	Various plant sources	[100]

these, Pb, Cd, Hg, and Cr were the most consistently reported across multiple studies and geographic settings.

The sources documented across the included studies were predominantly anthropogenic in nature, encompassing industrial and municipal waste streams, vehicle and fossil fuel emissions, battery and metal fabrication industries, agricultural runoff, unregulated waste disposal, and mining activities (Table 3). Several studies additionally identified food-related exposure pathways, with Pb detected in commonly consumed staples including matooke, potatoes, beans, cabbage, and tomatoes [16, 17]. Mercury contamination was notably associated with a broader range of diffuse sources, including atmospheric deposition, sand mining, metal welding, horticultural practices, and the improper disposal or burning of batteries [44, 95].

3.5 Ecological risks and environmental toxicology of heavy metals in Uganda

The risk level and toxicological impact of heavy metals on environment and food systems in Uganda are presented in Table 4.

Assessment of the ecological impacts documented across the included studies revealed that Pb, Cd, Hg, and Cr consistently attracted the highest severity ratings, reflecting

Table 4 Risk level and toxicological impact of heavy metals on environment and food systems in Uganda

Heavy metal	Contaminated food sources	Concentration (range-mg/kg)	Risk level	Key health effects	References
Lead (Pb)	Fish, vegetables, maize	0.5–2.3	High	Neurotoxicity, cognitive impairment, developmental deficits in children	[16, 39]
Cadmium (Cd)	Vegetables, grains	0.3–1.7	High	Kidney damage, osteoporosis, carcinogenicity	[109, 14]
Mercury (Hg)	Fish, water	0.01–0.5	Moderate–High	Neurological disorders, fetal developmental risks, food chain bioaccumulation	[44, 95]
Chromium (Cr)	Beef, vegetables	0.2–0.9	Moderate	DNA damage, respiratory and liver toxicity	[56, 72]
Nickel (Ni)	Maize, fish	0.4–1.5	Moderate	Carcinogenic potential, immune suppression	[28, 96]
Zinc (Zn)	Cereals, vegetables	3.5–7.0	Low–Moderate	Essential nutrient at low levels; digestive issues and immune suppression at high levels	[33], 84]

Concentrations are presented as reported in the original studies, without unit conversion or standardisation across studies. Ranges represent the minimum and maximum values documented for each metal-food matrix combination

their well-established environmental persistence, bioaccumulative potential, and broad ecosystem toxicity (Table 4). Lead contamination, sourced primarily from industrial waste, vehicle emissions, and battery production, was associated with contamination of drinking water sources, reduction of soil fertility, and toxicity to aquatic biota [40, 57].

Mercury contamination presented a particularly distinctive ecological risk profile. Predominantly sourced from artisanal and small-scale mining operations, fossil fuel combustion, and the improper disposal or burning of batteries, Hg was specifically associated with contamination of rivers and lakes, where its capacity for bioaccumulation in aquatic organisms establishes a progressive trophic transfer pathway into human food chains [44, 95]. This bioaccumulative dynamic distinguishes mercury from other metals in terms of ecological risk, as even relatively low environmental concentrations can translate into substantially elevated tissue burdens in fish and other aquatic organisms consumed by human populations.

Chromium, primarily introduced through industrial wastewater, tannery effluents, and the irrational use of agrochemicals, was flagged for its acute toxicity to aquatic organisms and its capacity to damage terrestrial vegetation [28, 114]. Cadmium, sourced from agricultural runoff, waste incineration, and industrial emissions, was specifically associated with entry into the food chain through plant uptake, accumulation in edible crops, and disruption of soil microbial communities essential for ecosystem functioning [64, 81].

3.6 Heavy metal contamination of food systems and reported human health implications

The contaminated food sources according to the reported heavy metals are presented in Table 4.

Analysis of food system contamination data revealed that heavy metals detected across Ugandan environmental matrices have demonstrably entered the food chain at concentrations with established human health significance, affecting a wide range of commonly consumed foods, including fish, vegetables, grains, beef, and maize flour (Table 4). Lead was detected in fish, vegetables, and maize at concentrations ranging from 0.5 to 2.3 mg/kg, levels associated with neurotoxicity, impaired cognitive development, and developmental deficits, particularly in children [16, 39]. While Bagumire et al. [16] noted that detected Pb levels in farmed fish remained below USFDA and EU regulatory limits at the time of assessment. Tagumira et al. [109] further warned that high levels of lead and cadmium in crops could cause severe clinical outcomes, including kidney failure and neurological disorders. Cadmium concentrations in vegetables and grains ranged from 0.3 to 1.7 mg/kg and were classified as high-risk, with documented associations with nephrotoxicity, osteoporosis, and carcinogenic effects following chronic dietary exposure [14, 109, 14] specifically found that several metals, including Cd, exceeded WHO/FAO safety recommendations in crops.

Mercury in fish and water was detected at concentrations of 0.01–0.5 mg/kg and classified as moderate-to-high risk, with neurological disorders, fetal developmental impairment, and progressive bioaccumulation in food chains identified as the primary health consequences [44, 95].

Across the food system, a consistent and concerning theme emerges. The anthropogenic sources driving environmental contamination were mainly through industrial activity, mining, unregulated waste disposal, and intensive agricultural practices. They function simultaneously as the proximate drivers of food chain contamination, creating an integrated and self-reinforcing exposure continuum from environment to table.

4 Discussion

The increasing prevalence of heavy metal contamination in Uganda's environment and food systems represents a critical and escalating public health challenge, particularly for vulnerable populations, including children, pregnant women, and communities dependent on subsistence agriculture and artisanal fishing.

Analysis of the regional distribution of heavy metal reporting across the 39 included studies revealed marked geographic disparities in research coverage, with the Central and Western regions accounting for the highest number of metal mentions. The Northern region had the fewest mentions nationwide. Documenting the frequency of each metal as mentioned across regions is important because it maps the current boundaries of scientific knowledge, revealing where research has been concentrated. This is critical, as the paucity of reports identifies regions where metal contamination has received limited scientific research.

The Central region dominated the reporting profile, with Pb mentioned most frequently. This finding is particularly alarming given the well-documented health risks associated with Pb exposure, including neurological disorders and developmental issues, particularly in vulnerable populations such as children and pregnant women [11, 21, 112] . The report on metals in the Central region is consistent with its status as Uganda's most urbanized and industrialized zone, where proximity to industrial activity, heavy traffic, and dense waste generation has drawn the greatest research attention [40, 58]. This pattern of urban-industrial zones attracting disproportionate research attention is well-established across sub-Saharan Africa. In Kenya, the majority of heavy metal contamination studies have been concentrated in Nairobi and its peri-urban agricultural belt, with rural and pastoralist regions receiving comparatively little investigative attention despite documented contamination risks from livestock dipping chemicals and informal mining [7, 55]. Similarly, in Nigeria, [39] observed that heavy metal research was overwhelmingly clustered around Lagos, Port Harcourt, and other industrial cities, leaving large agricultural and rural regions systematically undercharacterized. This is a structural research bias that mirrors Uganda's own geographic skew toward the Central region. In Ethiopia, Abebe et al. [1] found contamination in areas surrounding the Awash Valley industrial corridor. Highland agricultural regions were not reported despite their intensive use of agrochemicals.

The socioeconomic implications of this urban-industrial concentration of research are substantial. Densely populated peri-urban communities in Uganda's Central region mostly rely on locally grown vegetables and fish from urban water bodies. They face the highest and most diverse heavy metal exposure burden in the country, yet these are often low-income households with the least capacity to access alternative food sources or healthcare when contamination-related illness occurs.

Eastern Uganda showed a comparatively uniform distribution with most metals mentioned only once, suggesting that systematic heavy metal research in this predominantly agricultural region remains limited relative to its population size and farming activity. Northern Uganda was strikingly underrepresented, with only a single mention of aluminium across all 39 included studies, a finding that reflects a near-total absence of investigative research rather than non-contamination. This identifies the North as the most critical geographic gap in Uganda's current evidence base. A comparable situation has been documented in South Sudan, where the near-complete absence of environmental contamination research has left populations in mining and conflict-affected areas without any evidence base for health risk assessment or policy response [28], underscoring the broader regional pattern of research neglect in politically and economically marginalized areas.

At the national level, Pb accounted for the largest share of all metal mentions, followed by Cu, Cd, Cr, and Zn. The dominance of Pb in national reporting is consistent with findings across other Sub-Saharan African countries, indicating Pb as the most frequently reported heavy metal contaminant [3, 10, 28, 39]. These reports attributed its prevalence to the widespread use of electronic waste, contaminated water bodies, and food waste. Mercury accounted for only 6.00% of national mentions in Uganda. This is critical, given its exceptional bioaccumulative and neurotoxic properties. It is indicative that Hg remains substantially under-investigated relative to the magnitude of risk it poses. This underrepresentation of mercury in national monitoring data has been similarly noted in other countries in East Africa, including Tanzania and Ethiopia [39, 55]. These authors highlighted that despite extensive artisanal gold mining activity and documented mercury use in amalgamation processes, systematic mercury monitoring in food and environmental matrices remained critically sparse.

The presence of multiple heavy metals across various regions indicates a complex interplay of environmental factors and human activities contributing to contamination. The implications of these findings are profound, as heavy metal contamination poses significant risks to public health and the environment. Chronic exposure to heavy metals like lead and cadmium can lead to severe health issues, including neurological disorders, developmental problems in children, and increased cancer risks [11, 13, 25, 28, 28, 39, 43, 55, 112]. The detection of heavy metals in agricultural products, such as matooke and vegetables, raises concerns about food safety and security, especially for vulnerable populations [28]. Additionally, the presence of heavy metals in water sources can affect both human health and aquatic ecosystems, posing risks to biodiversity and ecosystem stability.

Despite the findings from our review, the reporting distributions in Uganda should be interpreted with the important caveat that the percentage figures reflect how frequently each metal was mentioned across the included studies rather than measured environmental concentrations. These gaps collectively underscore the urgent need for regionally targeted heavy metal investigations specifically designed to generate actual concentration data across all of Uganda's regions.

This review identified 13 heavy metals across the environmental and food matrices in Uganda, with Pb, Cd, Hg, and Cr emerging as the most consistently reported contaminants across multiple studies and geographic settings. The sources were overwhelmingly anthropogenic, encompassing industrial and municipal waste streams, emissions, unregulated waste disposal, and mining activities [14, 16, 39, 39, 55, 64, 77, 113].

The presence of these metals highlights the urgent need for stringent regulations on industrial practices and waste management to mitigate their release into the environment.

Anthropogenic activities, poor waste management, and inadequate environmental regulation emerge as the primary systemic drivers of heavy metal contamination in Uganda [15]. This pattern closely mirrors findings from comparable settings across sub-Saharan Africa. In Kenya, Mungai et al. [39] similarly documented that Pb and Cd contamination in peri-urban agricultural soils was primarily attributable to industrial discharges, vehicular emissions, and the use of phosphate fertilizers [7, 76]. In Tanzania, Bose-O'Reilly et al. [23]; Msigwa and Kassian [43] reported that artisanal and small-scale gold mining was the dominant driver of Hg contamination in soils and water bodies around mining settlements. This is consistent with reports identifying artisanal mining as a significant source of mercury contamination in Uganda [95].

In Ethiopia, tannery effluents and industrial wastewater were identified in previous studies as the principal sources of Cr and Cd contamination in agricultural soils irrigated with polluted water [2, 39]. This pattern parallels the role of industrial wastewater and agrochemical misuse in driving Cr contamination documented across the included studies in Uganda [28, 114]. Gottesfeld et al. [28] reported that urban soils and crops in industrialized zones contained elevated Pb and Cd concentrations attributed to battery recycling facilities in seven African countries, including

Cameroon, Ghana, Kenya, Mozambique, Nigeria, Tanzania, and Tunisia. This was similar to our findings, though vehicle emissions and uncontrolled waste incineration were also identified. The findings from Uganda align with global trends in heavy metal contamination, particularly in developing countries where industrialization and urbanization are rapid. For instance, studies in Nigeria have similarly reported elevated levels of lead and cadmium in urban soils and crops, linking these to industrial activities and emissions [39, 43]. In Kenya, research has shown that mining activities contribute significantly to heavy metal pollution in nearby agricultural lands [39, 43]. These reinforce the notion that heavy metal contamination is a widespread issue requiring coordinated efforts for effective management and mitigation strategies.

Mercury presented a particularly distinctive source profile in the Ugandan context, associated with atmospheric deposition, sand mining, metal welding, horticultural practices, and the improper disposal or burning of batteries [44, 95]. This diversity of mercury sources reflects its volatile and highly mobile environmental behaviour, distinguishing it from metals whose contamination is more tightly coupled to fixed industrial point sources. A comparable pattern of diffuse mercury sources was documented by [107] in Tanzania and [12] in Cameroon, where mercury contamination in lake sediments was attributed to both artisanal mining runoff and atmospheric deposition from regional industrial activity, demonstrating that mercury's environmental mobility creates contamination pathways that extend far beyond the immediate vicinity of point sources. Selenium, by contrast, was the only metal whose reported source was exclusively plant-based in Uganda [100], consistent with its predominantly geogenic and dietary origin reported in other regional agricultural contexts [28, 77], where selenium soil levels are governed primarily by parent rock composition rather than industrial inputs.

The convergence of industrial, agricultural, and waste-related source categories across the majority of identified metals carries profound socioeconomic implications. Heavy metals that share overlapping sources highlight co-exposure scenarios in which populations are simultaneously exposed to multiple toxic metals through soil, water, air, and food. The cumulative and potentially synergistic toxicity of such co-exposures generates healthcare costs, reduces workforce productivity through chronic illness and neurodevelopmental impairment, and diminishes educational outcomes in children. All these impacts further compound existing socioeconomic vulnerabilities in communities with limited access to healthcare and social protection [25, 28]. This multi-metal co-exposure dynamic has been similarly documented in Rwanda [28], South Africa [39], and the Democratic Republic of Congo [81], reporting that communities near mining sites were simultaneously exposed to Pb, Cd, As, and Hg through contaminated soils, water, and locally grown crops, with compounded health risks that single-metal assessments substantially underestimated. Animals in agricultural settings are similarly vulnerable, with bioaccumulation of heavy metals linked to reproductive failure, growth impairment, and increased mortality [6, 39], while livestock consuming contaminated feed or water introduce additional risks into the human food supply chain, threatening both subsistence livelihoods and commercial agricultural sectors [9, 43]. Heavy metals such as Pb, Cd, Mn, Hg, and Cr were prevalent in various environmental matrices in Uganda primarily as a consequence of anthropogenic activities [28, 39, 81, 113], highlighting the interconnectedness of human, animal, and environmental health as articulated by the One Health approach. This interconnectedness implies that Uganda cannot effectively protect public health through health sector interventions alone. Environmental regulation, agricultural policy, and waste governance must be simultaneously reformed within a coherent cross-sectoral framework.

Assessment of the ecological impacts documented across the included studies revealed that Pb, Hg, and Cd consistently attracted the high severity ratings, reflecting their well-established environmental persistence, bioaccumulative potential, and broad ecosystem toxicity. Pb contamination, sourced primarily from industrial waste, vehicle emissions, and battery production, was associated with contamination of drinking water sources, reduction of soil fertility, and toxicity to aquatic biota [40, 58]. These ecological impacts of Pb are consistent with findings from across sub-Saharan Africa. In Kenya, Macharia et al. [64] documented that Pb contamination from artisanal gold mining in Migori County had severely degraded soil quality and reduced yields of staple crops in surrounding agricultural areas, with contamination persisting in soils decades after initial mining activity. In South Africa, gold mining operations generated Pb and As contamination in soils and water bodies, affecting ecological communities and human health [86, 92]. In Nigeria, it was reported that oil spill-associated heavy metal contamination, including Pb, Ni, and V, had devastated mangrove ecosystems and coastal fisheries in the Niger Delta, with ecological recovery remaining incomplete decades after contamination events [28, 28]. This re-emphasizes that prevention through regulatory enforcement is far more effective and economically rational than post-contamination remediation.

Mercury contamination presented a particularly distinctive ecological risk profile in Uganda. Sourced from artisanal mining, fossil fuel combustion, and improper battery disposal, Hg contaminated rivers and lakes through bioaccumulation and biomagnification in aquatic food chains [44, 95]. Mpewo et al. [28] further corroborated this concern, noting that even relatively low environmental mercury concentrations can translate into substantially elevated tissue burdens in fish and aquatic organisms. This amplification effect has been extensively documented in East African lake systems. In East Africa, [26] reported that mercury concentrations in Nile perch from Lake Victoria exceeded safe consumption guidelines in samples from areas with intensive artisanal mining activity, despite relatively modest mercury concentrations in lake water. These findings illustrate the limitations of water-based monitoring as a proxy for human exposure risk in mercury-affected aquatic systems. These findings from neighbouring countries reinforce the urgency of implementing tissue-based biomonitoring of sentinel fish species in Uganda's major lake systems, where comparable contamination dynamics are likely operating but remain uncharacterized. The ecological threat posed by mercury extends across interconnected aquatic ecosystems serving as critical food and income sources for millions of individuals in Uganda. This makes mercury management simultaneously an environmental, nutritional, and economic priority.

Cadmium, sourced from agricultural runoff and waste incineration, entered the food chain through plant uptake and disrupted soil microbial communities essential for ecosystem nutrient cycling [64, 81]. Although there is a paucity of reports on Cd in East Africa, its persistence in contaminated agricultural soils has been reported. Cadmium was previously identified as one of the major heavy metal contaminants in urban soils of Africa, exceeding internationally permissible limits and posing substantial environmental and human health risks [64]. In Zambia, cadmium was one of the metals identified in the assessment of contamination from copper-cobalt mining operations in the Copperbelt. It penetrated agricultural soils and posed chronic dietary health risks to local communities [28]. The findings from [18], regarding the contamination of surface and groundwater with trace metals, underscores the potential for widespread ecological disruption and long-term health consequences. The accumulation of toxic metals in crops, fish, and water sources threatens the health of vulnerable populations, especially children, who are more susceptible to the adverse effects of heavy metal exposure [19, 20, 43].

The ecological findings from Uganda align closely with evidence from comparable East African and sub-Saharan African contexts, confirming that heavy metal contamination is a pervasive transboundary challenge driven by shared structural conditions of inadequate industrial regulation, expanding artisanal mining, and uncontrolled waste disposal. Collectively, these findings illustrate the multifaceted nature of heavy metal contamination across various ecosystems in Uganda, necessitating urgent attention and intervention. There is a need to develop harmonized East African environmental monitoring frameworks and coordinated cross-border pollution control strategies. To mitigate ecological risks, several evidence-based remedial interventions warrant prioritization. This includes, but is not limited to, phytoremediation using hyperaccumulator species such as *Thlaspi caerulescens* for cadmium, bioremediation using metal-tolerant microbial consortia to restore contaminated soils, biochar amendment to immobilize Pb and Cd in agricultural soils, and constructed wetlands using locally available macrophytes to intercept heavy metal-laden runoff before it reaches Uganda's lake and river systems.

Analysis of food system contamination data revealed that heavy metals detected across Ugandan environmental matrices have demonstrably entered the food chain at concentrations with established human health significance, affecting fish, vegetables, grains, beef, and maize flour. These are foods that collectively constitute the dietary foundation for the majority of Uganda's population. This environment-to-food transfer pathway implies that ecological contamination is a proximate and ongoing driver of dietary heavy metal exposure. Particularly for low-income households with limited dietary diversity, there is a limited capacity to dilute their exposure across a range of food sources. The detection of lead, mercury, and cadmium in farmed fish [16] and of heavy metals in agricultural produce [39] indicates that these pollutants are bioaccumulating in the food chain and posing significant health risks to consumers. These findings are consistent with a growing body of evidence from across East Africa and sub-Saharan Africa documenting the transfer of environmentally deposited heavy metals into human food systems at health-significant concentrations.

Lead was detected in fish, vegetables, and maize at concentrations of 0.5–2.3 mg/kg, levels associated with neurotoxicity, impaired cognitive development, and developmental deficits in children [16, 39, [16] noted that Pb levels in farmed fish remained below USFDA and EU regulatory limits, the authors raised substantive concerns about food safety standards in relation to export market requirements and the cumulative dietary burden on local consumers. In Kenya, Pb levels were elevated in kale irrigated with untreated industrial wastewater, indicating significant transfer of lead contamination from polluted irrigation sources into edible vegetables [55]. In Tanzania, Pb contamination in rice and maize grown in peri-urban farming areas was at concentrations predisposing daily consumers to health risk [43, 64]. Similarly, in Ethiopia, elevated blood lead levels in children from urban areas where vegetable consumption was common [28, 55]. These reports established a direct epidemiological link between dietary lead exposure from contaminated produce and measurable neurodevelopmental consequences. [109] further warned that high levels of lead and cadmium in crops could precipitate kidney failure and neurological disorders in Uganda.

Given that Pb has no established safe threshold for developmental neurotoxicity [112], these cross-regional findings highlight the widespread presence of dietary lead exposure from contaminated staple foods across sub-Saharan Africa. This establishes lead contamination as one of the most consequential yet underregulated public health threats facing populations in the region.

Cadmium (Cd) concentrations in vegetables and grains (0.3–1.7 mg/kg) were classified as high-risk, with nephrotoxicity, osteoporosis, and carcinogenicity documented following chronic dietary exposure [14, 109, 14] found that Cd exceeded WHO/FAO safety recommendations in crop tissues, particularly in leafy tissues and short-cycle vegetable crops. This finding is consistent with findings from Kenya, where [77] reported that Cd concentrations were elevated in soils near industrial areas, raising concerns that long-term consumption of locally grown vegetables cultivated on these contaminated soils may pose health risks to humans and animals. This pattern directly parallels the crop-type differential reported by [14] in Uganda. Previous studies in Zambia identified Cd and Pb contamination in maize grain that exceeded FAO/WHO safety limits, posing significant dietary health risks, although chicken manure-based soil amendments showed potential to reduce their accumulation in maize and lower associated food safety risks [43]. In contrast, Cd was ranked among the least concentrated heavy metals detected in cassava and plantain from Tarkwa, Ghana. It was acknowledged that its presence in staple food crops still represents a potential long-term dietary health risk due to cumulative exposure through regular consumption, despite its relatively low levels [22].

In our review, apart from Pb and Cd, Mercury in fish and water (0.01–0.5 mg/kg) was classified as moderate-to-high risk, with neurological disorders, fetal developmental impairment, and food chain bioaccumulation identified as primary health consequences [44, 95, 44] identified fish consumption as the principal human mercury exposure pathway in Lake Nabugabo, Uganda, with pregnant women, nursing mothers, and young children facing the greatest neurodevelopmental vulnerability. The communities situated around Lakes Victoria, Albert, and Kyoga face a disproportionate and largely unquantified mercury burden that existing food safety monitoring systems appear inadequate to address. This situation is directly comparable to Lake Victoria on the Tanzanian and Kenyan shores. [26] demonstrated that mercury concentrations in Nile perch and tilapia exceeded WHO consumption guidelines in samples from artisanal-mining catchments. Similarly, [92], that mercury from artisanal and small-scale gold mining (ASGM) contaminates terrestrial and aquatic ecosystems surrounding mining communities in some East Asian countries including Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, and Thailand (Southeastern Asian countries), creating potential food-chain exposure risks through contaminated water and aquatic food sources, with nearby populations facing significant health risks from chronic mercury exposure. Most of these clinical manifestations represent the final health outcomes of a bioaccumulation process in which mercury released into the environment accumulates in aquatic ecosystems and ultimately reaches humans through the consumption of contaminated fish.

The findings of our review further demonstrate that anthropogenic activities simultaneously drive environmental and food contamination. This creates a self-reinforcing exposure continuum from environment to table. However, the current regulatory frameworks in Uganda remain insufficiently equipped to address. Heavy metal contamination in food systems is therefore not an isolated local issue. It is a systemic and region-wide public health challenge rooted in weaknesses in environmental governance. Addressing this challenge will require coordinated interventions, including stricter industrial waste management policies, systematic food safety monitoring across production and processing stages, safer food processing, improved composting practices, and public health awareness campaigns. Sustainable remediation approaches such as chelation-assisted phytoremediation, biochar and zeolite soil amendments, nanofiltration systems, and constructed wetlands for irrigation water purification should also be prioritized to reduce heavy metal exposure across the food chain.

Considering all the themes discussed, this is the first systematic review to synthesize evidence on heavy metal contamination across environmental and food systems in Uganda using the PRISMA framework and PICOS criteria. It provides a structured and reproducible evidence base. The geographic and thematic assessment across Uganda's four administrative regions and the reported heavy metals offer broad insight into the national contamination burden. Additionally, integrating ecological risk assessment, food system toxicology, and regional distribution analysis using a single review enabled cross-domain insights not achievable through single-focus studies.

However, several limitations should be acknowledged when interpreting these findings. First, regarding metal coverage, this review did not include certain heavy metals and metalloids, specifically silver, antimony, barium, beryllium, tin, and gallium, because the available primary studies in Uganda focused predominantly on commonly investigated contaminants such as lead, cadmium, mercury, chromium, copper, and zinc. Consequently, our findings may not capture the full spectrum of emerging or underreported metal contaminants present within Ugandan environmental and food systems.

Second, methodological heterogeneity across 39 included studies limited direct quantitative comparisons. Variability existed in analytical techniques (ranging from flame atomic absorption spectrometry to inductively coupled plasma mass spectrometry), sampling approaches (different depths, seasons, and matrices), detection limits (varying by instrument and laboratory), and reporting standards (some studies reported dry weight, others fresh weight). These differences constrain the feasibility of meta-analysis and introduce measurement bias.

Third, most included studies employed cross-sectional designs, capturing contamination at single time points. This design limitation prevents assessment of long-term exposure dynamics, seasonal variability, and cumulative health effects that typically require longitudinal data spanning multiple years.

Fourth, geographic representation was markedly uneven. Studies concentrated heavily in Central Uganda (44.8% of metal mentions) and Western Uganda (31.3%), while Northern Uganda remained severely underrepresented (only 1.50% of metal mentions). This geographic skew limits national generalizability and means that the absence of contamination reports from Northern Uganda should not be interpreted as evidence of absence of contamination.

Fifth, bioavailability assessments were performed inconsistently. Only a minority of included studies measured metal speciation or bioaccessible fractions, whereas total metal concentrations, which dominated the available data, may overestimate actual health risks because they do not reflect the proportion of a metal that is absorbed following ingestion or inhalation.

Finally, most studies did not adequately control for potential confounding factors such as age, nutritional status, smoking, occupational exposure, and co-exposure to multiple metals, all of which can modify heavy metal toxicokinetic and health outcomes. This limitation is particularly relevant given the multi-metal co-exposure patterns documented across several Ugandan regions.

These limitations collectively highlight important priorities for future research, which are detailed in the recommendations section below.

5 Conclusion

This systematic review provides a comprehensive assessment of heavy metal contamination in environmental and food systems in Uganda based on evidence from 39 studies. Thirteen heavy metals were identified, with lead, cadmium, mercury, and chromium emerging as the most prevalent and toxicologically significant contaminants. The major contamination sources were anthropogenic, including industrial and municipal waste, mining activities, vehicle emissions, agricultural runoff, and poor waste disposal practices, reflecting broader environmental governance challenges observed across sub-Saharan Africa. Regional analysis showed that Central Uganda documented extensive heavy metal contamination associated with urbanization and industrialization, whereas Northern Uganda remains understudied.

Lead (17.9%) was the most frequently reported contaminant nationally. Mercury, despite lower reporting frequency, remains a major concern. This is because of its bioaccumulative and neurotoxic properties, particularly in aquatic ecosystems and artisanal mining areas.

Ecologically, heavy metals threaten soil fertility, aquatic biodiversity, food security, and agricultural sustainability. In food systems, contamination of staple foods with lead, cadmium, and mercury presents important public health risks, especially for children and pregnant women. These findings indicate that heavy metal contamination in

Uganda is a systemic environmental and public health challenge driven by weaknesses in environmental regulation, industrial oversight, and waste management.

Addressing this challenge requires coordinated and evidence-based interventions, including strengthened environmental monitoring, targeted regional investigations, sustainable remediation strategies, and improved food safety surveillance within a One Health framework. Without urgent action, heavy metal contamination will continue to undermine public health, ecosystem integrity, agricultural productivity, and socioeconomic development in Uganda.

6 Recommendations

6.1 Strengthen industrial emission and waste management regulations

The National Environment Management Authority and the Ministry of Water and Environment should strengthen enforcement of environmental regulations governing industrial emissions, effluent discharge, and waste disposal, with particular emphasis on controlling lead and mercury pollution. The Ministry of Trade, Industry, and Cooperatives should regulate the importation and use of lead-containing products, while local governments should establish protective buffer zones between industrial facilities and nearby agricultural or residential areas.

6.2 Enhance national food safety monitoring systems

The Uganda National Bureau of Standards, Ministry of Health, and Ministry of Agriculture, Animal Industry, and Fisheries should implement routine heavy metal surveillance of fish, vegetables, grains, beef, and other staple foods across production, processing, and market stages. National maximum residue limits consistent with World Health Organization/Food and Agriculture Organization and Codex Alimentarius standards should be formally adopted and enforced. Export certification agencies should also incorporate mandatory heavy metal screening into pre-export quality assurance protocols.

6.3 Promote safer agricultural practices

The Ministry of Agriculture, Animal Industry and Fisheries, and the National Agricultural Research Organisation should promote agricultural practices that minimize heavy metal accumulation in soils and crops. This should include reducing the use of cadmium-containing phosphate fertilizers, encouraging soil amendments such as biochar and lime to reduce metal bioavailability, and implementing routine soil testing programs in farming communities. Land-use regulations restricting crop cultivation on contaminated industrial and mining sites should also be strengthened and enforced.

6.4 Expand public education and risk communication

The Ministry of Health, in collaboration with the Ministry of Education and Sports, should integrate heavy metal awareness into school curricula, community health programs, and agricultural extension activities. Public awareness campaigns delivered through radio, television, social media, and local language platforms should target high-risk populations, including farmers, fishermen, food vendors, and mining communities. Partnerships with Non-Governmental Organizations and civil society organizations should be strengthened to support community-level risk communication and health promotion initiatives.

6.5 Establish sustainable environmental and water monitoring programs

The Ministry of Water and Environment should establish a nationwide heavy metal surveillance program for major rivers, lakes, and drinking water systems, with priority focus on mercury and lead contamination in aquatic food chains. The National Water and Sewerage Corporation should integrate routine heavy metal screening into water quality monitoring frameworks, while the National Environment Management Authority should conduct periodic environmental audits of industrial and mining operations located near water bodies. International partners such as the World Health Organization, United Nations Children's Fund, and United Nations Environment Programme should be engaged to provide technical and financial support for sustainable national monitoring and remediation initiatives.

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